AMR 2017

NETL/DOE Award No. DE-EE0005981

High Efficiency VCR Engine with Variable Valve Actuation and new Supercharging Technology

June 8, 2017

Charles Mendler, ENVERA	PD/PI
David Genise, EATON	Program Manager & PI
Austin Zurface, EATON	Valvetrain
Matthew Williams, MAHLE	Dynamometer testing

ENVERA LLC

Mill Valley, California

Tel. 415 381-0560

Project ID ACS092

Overview

Timeline

Start date		April 11, 2013
End date		September 30, 2017
Percent complete[1]		
	Time	93%
	Budget	89%

Barriers & Targets

Vehicle-Technology Office Multi-Year Program Plan

Relevant Barriers from VT-Office Program Plan:
- Lack of effective engine controls to improve MPG
- Consumer appeal *(MPG + Performance)*

Relevant Targets from VT-Office Program Plan:
- Part-load brake thermal efficiency of 31%
- Over 25% fuel economy improvement – SI Engines
- *(Future R&D: Enhanced alternative fuel capability)*

Budget

Total funding	$ 2,784,127
Government	$ 2,212,469
Contractor share	$ 571,658

Expenditure of Government funds
June 2017 estimate $ 1,971,595

Partners

Eaton Corporation
Contributing relevant advanced technology R&D as a cost-share partner
MAHLE for Development and testing

Project Lead

ENVERA LLC

1. Through June 2017 estimate

Relevance

Research and Development Focus Areas:

Variable Compression Ratio (VCR)	*Approx. 8.2:1 to 17.6:1*
Variable Valve Actuation (VVA)	*Atkinson cycle and Supercharging settings*
Advanced Supercharging	*High "launch" torque & low "stand-by" losses*
Systems integration	

Objectives

40% better mileage than V8 powered van or pickup truck without compromising performance. *GMC Sierra 1500 baseline MY 2014.*

Relevance to the VT-Office Program Plan:

Advanced engine controls are being developed including VCR, VVA and boosting to attain high part-load brake thermal efficiency, and exceed VT-Office Program Plan mileage targets, while concurrently providing power and torque values needed for consumer appeal.

Milestones

Description	Milestone/ Go/No-go	Month/year	Status:
Feasibility analysis			
VCR	Milestone	Q2 2013	Complete
Valvetrain	Milestone	Q2 2013	Complete
Boosting			
Preliminary	Milestone	Q2 2013	Complete
GTPower modeling	Go/No-go	Q4 2014	Complete
Base engine specifications	Milestone	Q2 2013	Complete
Crankcase CAD and FEA	Go/No-go	Q3 2015	Complete
Crankcase castings	Milestone	Q4 2015	Complete
Crankcase Machining	Milestone	Q2 2016	Complete
Engine assembly	Go/No-go	Q4 2016	Complete
Testing: 2000 rpm 100 Nm		Q2 2017	Complete
12 map points		Q2/3 2017	
GTDrive fuel economy projections		Q3 2017	

Technological Approach

Approach for attaining high mileage

- Combine aggressive engine down-sizing with high-efficiency Atkinson cycle technology.

Approach for maximizing power and torque, e.g., Enabling technologies for aggressive engine down-sizing

- VCR
- Cam profile switching
- Advanced boosting

Development Strategy

Phase 1
Feasibility analysis, including:

• Variable compression ratio, VCR	Envera
• Variable valve actuation, VVA	Envera/Eaton
• Advanced boosting feasibility	Envera/Eaton
• GTPower computer modeling	Envera

Phase 2
Engine design / analysis / build

• VCR crankcase	Envera
• VVA, cylinder head, pressure sensing	Eaton
• Supercharging	Eaton
• Engine assembly	Envera

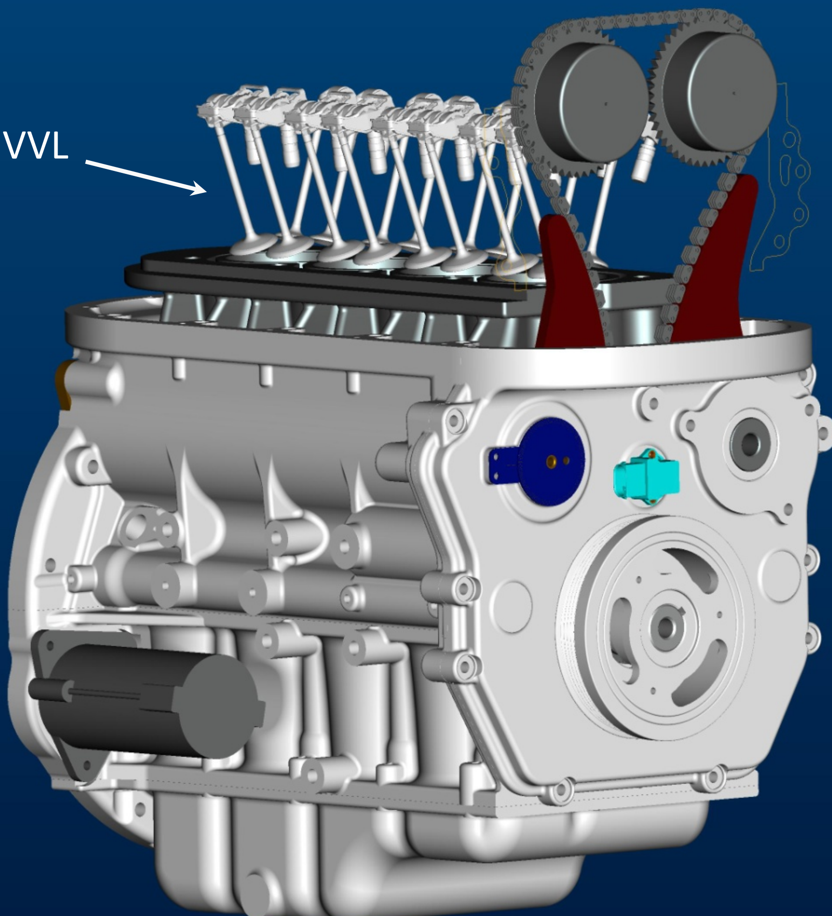
Phase 3
Engine Validation / Milestone Testing

• Development testing	MAHLE
• Mechanical systems validation assessment / reporting	Envera
• GT-Power / GT-Suite: BSFC & MPG projections	EngSim
• "Value engineering" as needed for achieving Targets	Envera

Envera VCR Engine

2.4L Engine Build & Test Setup

Envera VCR



VCR actuator mounting pad, position sensor, and optional dial.

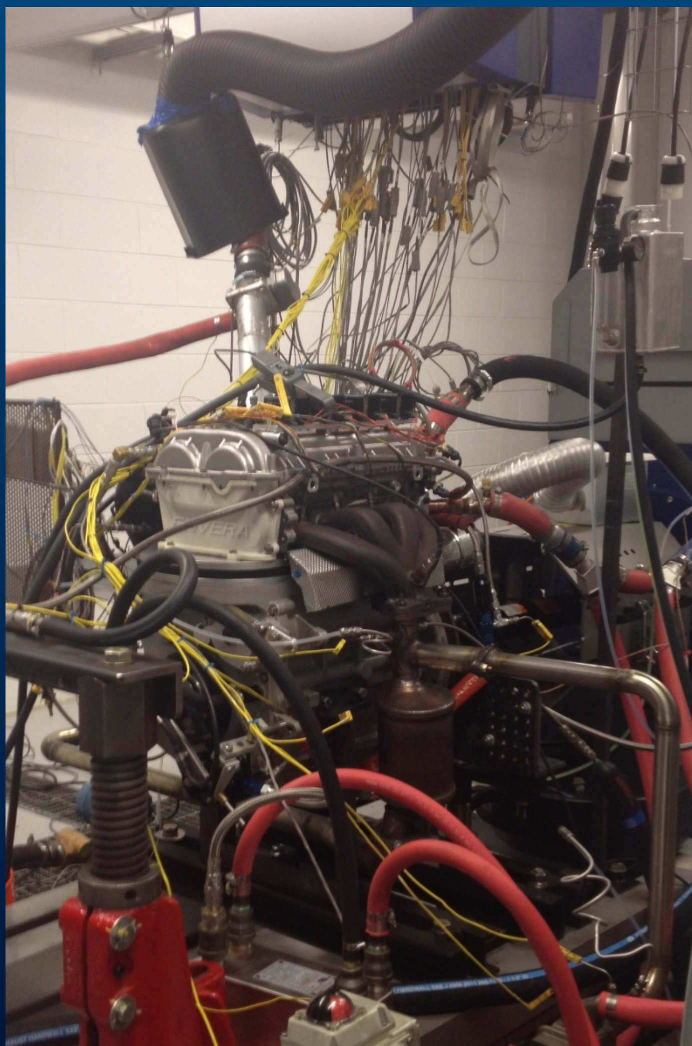
~Stock engine length and width.

Valve chain, front pulley and transmission can retain stock location.

Much narrower than V6.

Engine hardware is easier to see in CAD than in test cell photos. CAD pictures of the engine are provided in the backup slides.

Test Setup at MAHLE



ENVERA VCR engine on test at MAHLE

Test cell instrumentation includes:

- AC engine dynamometer
- Kistler 6052 pressure transducers & amps.
- AVL IndiCom combustion analysis
- AVL PUMA data compilation
- AVL AMA i60 emissions measurement

Test Setup

Indicating sensors are installed in the GDI fuel injector sockets.

PFI fuel injectors are mounted in an intermediate manifold.

The PFI injectors are targeted at the back of the intake valves.

VCR Engine Specifications

Displacement	2.4 L	
Bore	88.5 mm	
Stroke	97.6 mm	Nominal, minor shift with VCR
Bore center	96.0 mm	
Bore offset	10.5 mm	
Rod center length	166.0 mm	
Main bearing diam	55.0 mm	
Connecting rod bearing diam	50.8 mm	
Compression ratio	17.6	Maximum
	8.2	Minimum
Cylinder head	GM 2.5L MY 2014 LKW	
	DOHC	
	Eaton cam profile switching, intake	
	Dual cam phasers	
Fuel injectors	PFI: Bosch EV14	
Fuel	93 octane, pump grade with lab cert heating value	
Oil	10w 30 Mobil 1	
Ignition coils	AEM 103 MJ coil near plug	
EGR	Cooled external loop	
Oil pump	Barnes Systems, cog belt drive, wet sump	
Water pump	Electric, shop driven	

Cam Timing Values

EATON - ENVERA VVL CAM TIMINGS
All values at 1.00 mm lift

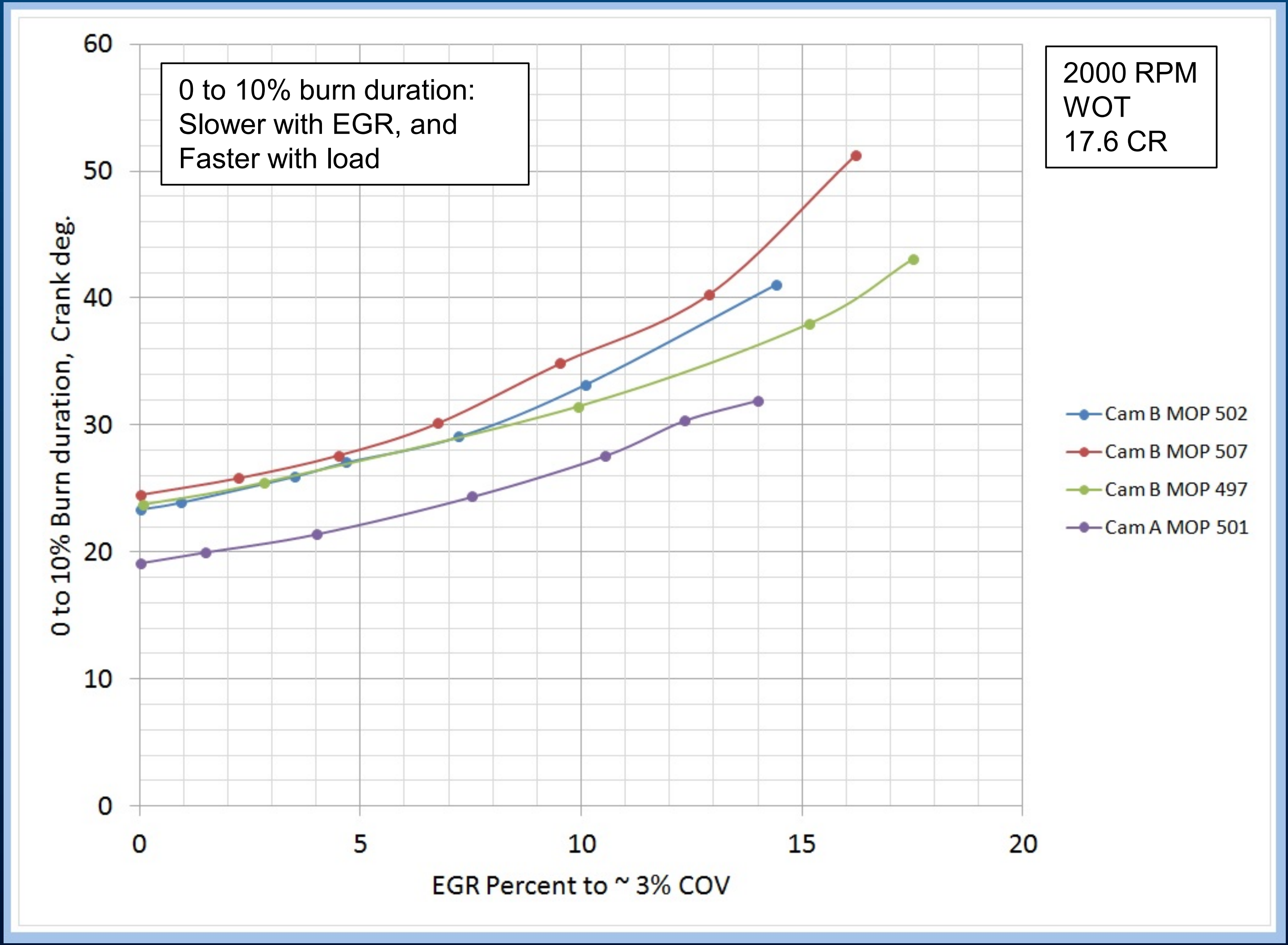
CAMSHAFTS	STOCK		BUILD A		BUILD B		BUILD C	
	Light load	Torque	Atkinson	Torque	Atkinson	Torque	Atkinson	Power
Intake Cam	**IN-S**		**IN-A**		**IN-B**		**IN-C**	
Duration	**246.2**	**200.0**	**246.2**	**200.0**	**254.2**	**183.1**	**280.0**	**214.0**
IVO	378.3	334.0	378.3	334.0	380.6	346.2	378.3	334.0
IVC	624.5	534.0	624.5	534.0	634.8	529.3	658.3	548.0
MOP	501.4	434.0	501.4	434.0	507.7	437.8	518.3	441.0
Exhaust Cam	**EX-S**		**EX-A**		**EX-B**		**EX-B**	
Duration	**186.0**	**186.0**	**213.7**	**213.7**	**200.4**	**200.4**	**200.4**	**200.4**
EVO			176.0	175.0	180.5	199.5	180.5	199.5
EVC			389.7	388.7	380.9	399.9	380.9	399.9
MOP			282.9	281.9	280.7	299.7	280.7	299.7

IVO Intake valve opening
IVC Intake valve closing
MOP Maximum open point
EVO Exhaust valve opening
EVC Exhaust valve closing

Test Results

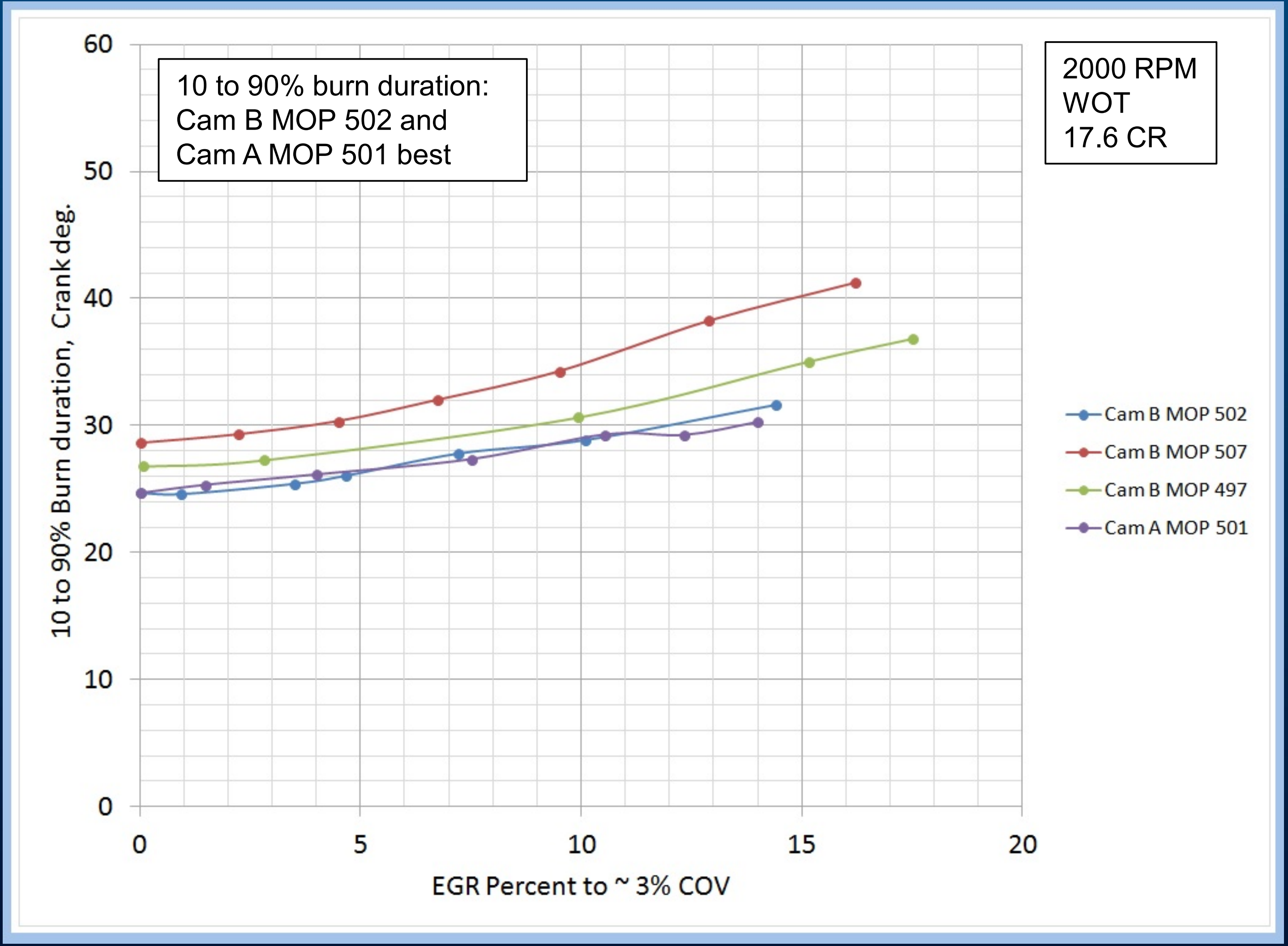
Test Results

Combustion burn rate, First 10% burnt



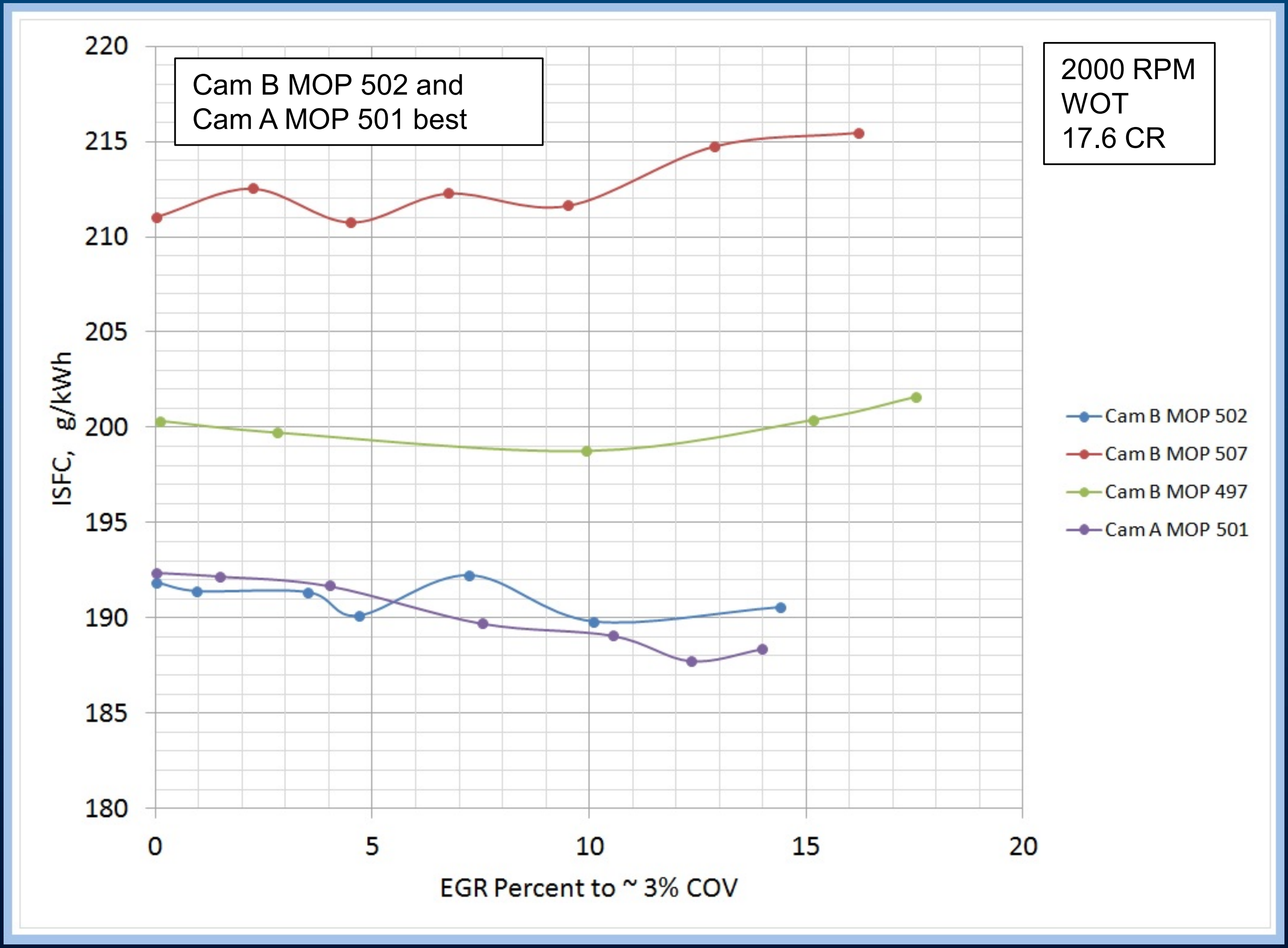
Test Results

Combustion burn rate, 10% to 90% burnt



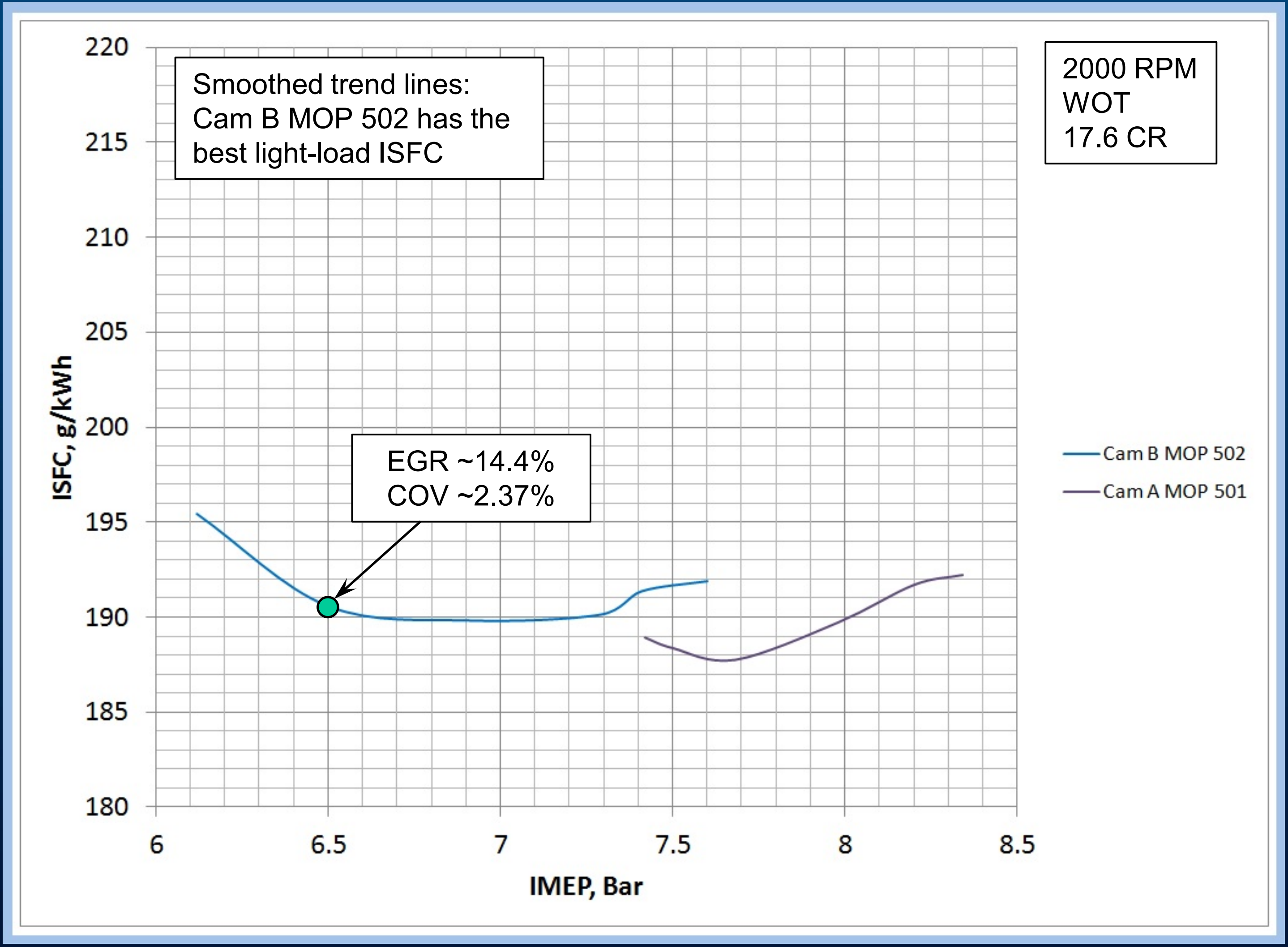
Test Results

Indicated specific fuel consumption vs. EGR



Test Results

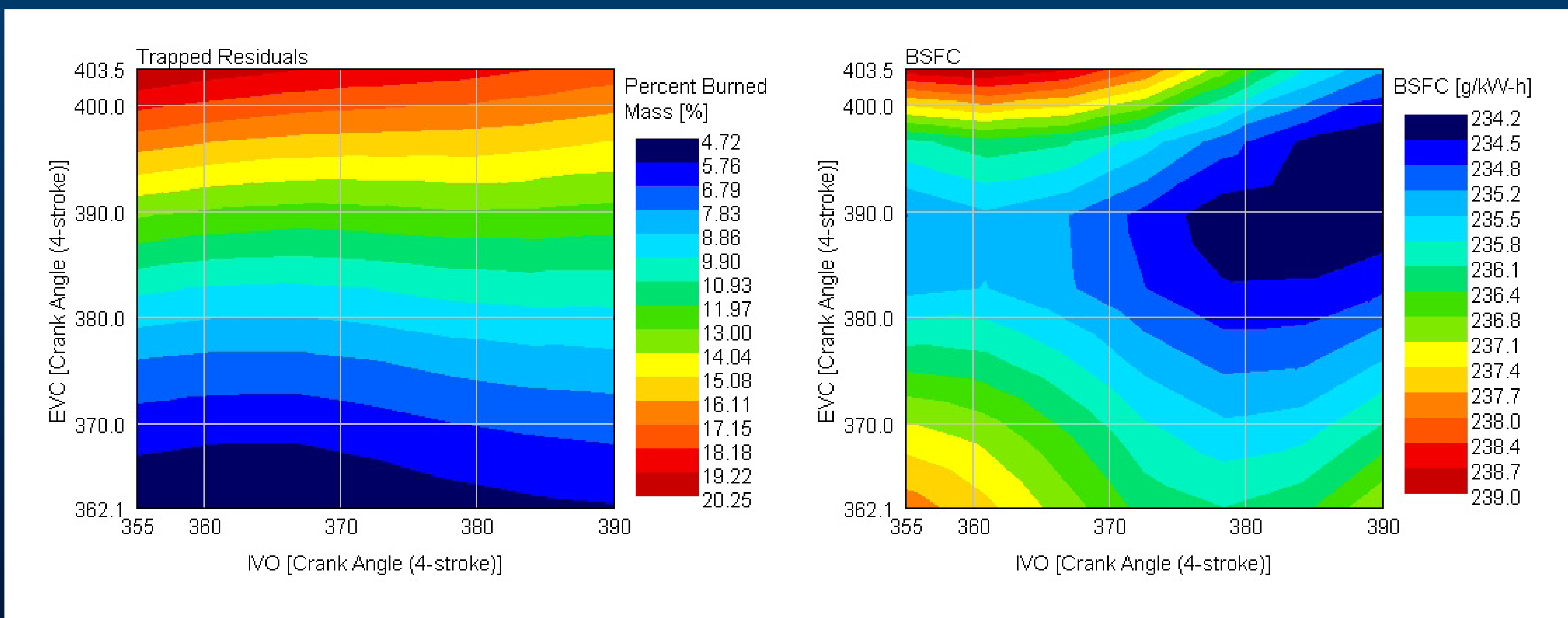
Indicated specific fuel consumption vs. IMEP



GTPower Projections

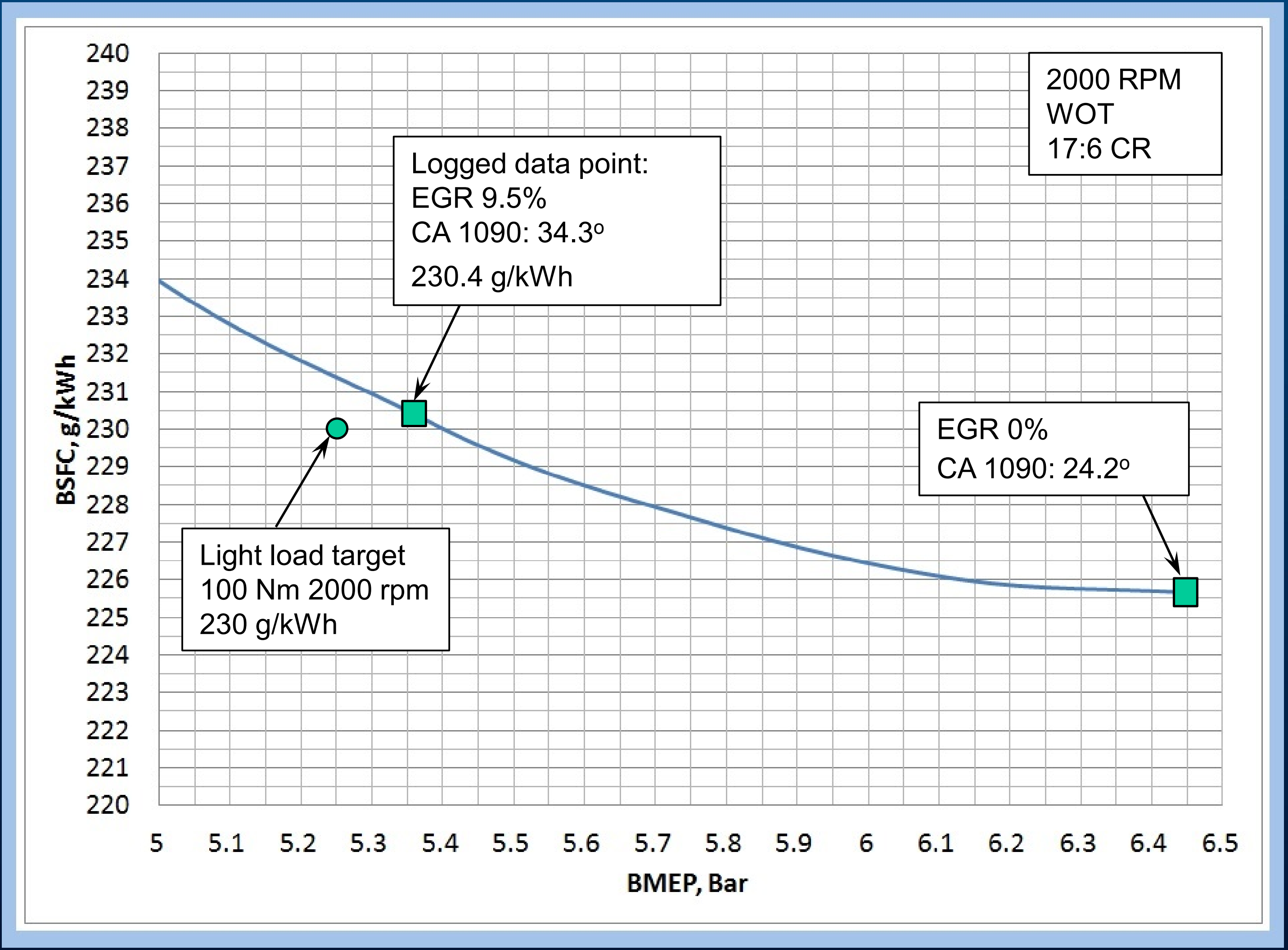
Near-conventional EGR dilution values provide best results

Test data supports the earlier GTPower projection that best part load efficiency occurs with about 11% to 15% EGR and Atkinson Cycle cam timing (late intake valve closing).



100 Nm, 2000 rpm, 18:1 CR

BSFC vs. BMEP Test Results
Cam B with Phase Shifting



2017 R&D Plan

Light-load development:

- Light load settings will be developed using GTPower with the objective of attaining 230 g/kWh @100 Nm 2000 rpm.
- An EGR rate of 11 to 15% will be used, as this range provided the best results with Cam B MOP 502.
- The Atkinson cycle will be slightly increased (later intake valve closing) relative to Cam B MOP 502 to slightly shift the BSFC curve to lighter loads. New cams will be made as needed.
- Steps will be taken to lower FMEP, including better sizing of the oil pump and lighter weight oil if practical. *See page 27 for additional details*

2017 R&D Plan

Development & BSFC Mapping:

- The engine will be optimized with GTPower then retested at approximately 12 load/speed conditions , including both supercharged and naturally aspirated settings.

- A BSFC map will be generated from the test data and GTPower. Fuel economy of a full-size pickup truck will then be modeled using GTDrive to evaluate potential benefits of the VCR engine.

- Engine friction will be mapped, and estimates of actuator power consumption will be updated using the engine load cycle generated with GTDrive for the full-size pickup truck.

2017 R&D Plan

Preliminary load/speed conditions to be tested:

- Idle
- 2 bar bmep @ 2000 rpm
- 5.25 bar bmep @ 2000 rpm
- 20% maximum load @ 2000 rpm
- Peak efficiency
- Max torque, 1500 rpm to 6500 rpm / Maximum power
- Additional points as needed for GTPower/GTDrive modeling

Development Progress

Development Progress for VCR

ENVERA VCR PROTOTYPE ENGINE		I	PHASE II	PHASE III
TIME LINE		BUDGET PERIOD 1		BP 2
CALANDAR TIMELINE		2013 / 2014 / 2015 / 2016		2017
Timing dependent on DOE/NETL award and kick-off meeting		Q1 Q2 Q3 Q4 / Q1 Q2 Q3 Q4 / Q1 Q2 Q3 Q4 / Q1 Q2 Q3 Q4		Q1 Q2 Q3
PHASE II	**VCR PROTOTYPE ENGINE BUILD**			
Task 8	VCR Crankcase Design and Engineering			
Subtask 8.1	CAD/FEA: Cranktrain and VCR Cradle			
Subtask 8.2	CAD/FEA: Crankcase with Bedplate		Completed	
Subtask 8.3	Thermal-CFD: Cooling circuit			
Subtask 8.4	CAD: Front Cover, Oil pan, remaining Components			
Task 9	Engine Build			
Subtask 9.1	Procure Crankshaft, Pistons and Connecting Rods			
Subtask 9.2	Rapid Prototype Castings			
Subtask 9.3	Machine Castings and Other Components			
Subtask 9.4	Purchase Components			
Subtask 9.5	Engine Pre/Assembly and Functionality Checks			
Task 10	Advanced Supercharger			
Subtask 10.1	Design and Engineering			
Subtask 10.2	Hardware Prototyped			
Subtask 10.3	I/O Controls Specification			
Task 11	Valve actuation			
Subtask 11.1	Design and Engineering			
Subtask 11.2	Hardware Prototyped			
Subtask 11.3	Sensor installation			
Subtask 11.4	I/O Controls Specification			
Task 12	Engine Management Advanced Set-up			
Task 13	Required DOE Reporting, meetings, presentations			
PHASE III	**ENGINE AND VEHICLE VALIDATION TESTING**			
Task 14	Engine Management and CV Calibration			
Subtask 14.1	Engine Management and Base Calibration			
Subtask 14.2	GTPower development / New Cams			
Subtask 14.3	Calibration / Engine BSFC Map Produced			
Task 15	Test Vehicle Simulation			
Task 16	Cylinderhead Advanced Development			
Task 17	Valvetrain development			
Task 18	Value Engineering			
Task 19	Required DOE Reporting, meetings, presentations			

Progress for VCR

Development Status Summary:

- Design and build of the Envera VCR Engine has been completed.
- The first round of engine testing has been completed. The light-load engine efficiency was ~231.4 g/kWh @2000 rpm, 100 Nm, close to the program target of 230 g/kWh.
- Testing at approximately 12 map points is scheduled for mid 2017.

Collaboration

Collaboration:

Eaton is currently collaborating with ENVERA on the project as a subcontractor.
Eaton is contributing relevant advanced technology R&D as a cost-share partner.
Eaton R&D development areas include the VVA and boosting.
MAHLE Powertrain is conducting development testing
EngSim is conducting GTPower and GTDrive modeling on a cost-share basis
Hasselgren Engineering is providing build support on a cost-share basis
ADEM LLC is providing general machining support

We welcome interest from the OEs, component manufacturers, and other R&D organizations.

Previous Reviewer Comments

AMR Reviewer comments from 2016

1. Actuator friction (FMEP) needs to be considered.

   Actuator power consumption was evaluated under a prior DOE contract, and included both computer modeling and rig testing.

   Actuator power consumption was estimated to be about 400 watts for an actuator capable of adjusting CR from minimum to maximum in less than 1 second.

   Because the actuator time per adjustment is short (less than 1 second), net power consumption is relatively small. An actuator firing every 90 seconds was estimated to have an average power consumption of about 4.5 watts.

Previous Reviewer Comments

AMR Reviewer comments from 2016

2. Friction increase due to higher cylinder pressure needs to be considered.

   FMEP values will be mapped during the second round of testing to quantify change of FMEP with change of CR.

   Higher peak cylinder pressures will lead to higher friction values, all else being equal.

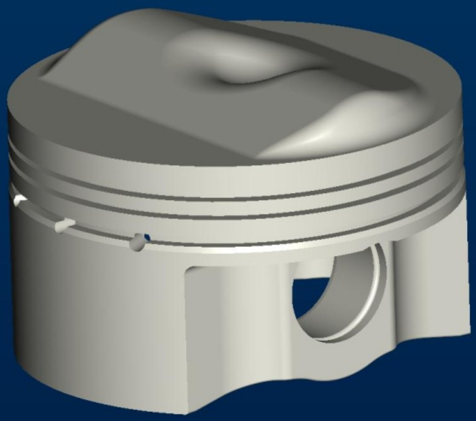
   However, VCR enables maximum cylinder pressure to be reduced, enabling smaller main and rod bearings to be used relative to other highly rated engines.

Previous Reviewer Comments

AMR Reviewer comments from 2016

3. The combustion chamber shape will be poor due to the high CR requirement.

   Through carful design Envera achieved a relatively good piston shape.



Previous Reviewer Comments

AMR Reviewer comments from 2016

4. A more in depth analysis is needed of the combustion process, such as moving geometry CFD and single cylinder engine development testing.

   The first round of testing demonstrated reasonably good combustion burn rates. Burn rates at 6.4 bar bmep were:

CA 0010	23.5^{o} crank	*First 10% burned*
CA 1090	24.2^{o} crank	*10% to 90% burned*

Previous Reviewer Comments

AMR Reviewer comments from 2016

5. Why not use variable valve control to vary the effective compression ratio?

   The effective compression ratio can be lowered by closing the intake valves very late to trap less air in the cylinders. With less trapped air, engine power is also reduced.

   But a low compression ratio at light load is not what is desired for improving efficiency.

   A high compression ratio is desired at light load. This high compression ratio can be provided with the VCR.

Summary

Summary:

- The first round of engine testing has been completed. The light-load engine efficiency was ~231.4 g/kWh @2000 rpm, 100 Nm, close to the program target of 230 g/kWh.

- The engine will next be optimized with GTPower then retested at approximately 12 load/speed conditions , including both supercharged and naturally aspirated settings.

- A BSFC map will be generated from the test data and GTPower. Fuel economy of a full-size pickup truck will then be modeled using GTDrive to evaluate potential benefits of the VCR engine.

Summary

Summary: *Continued*

- Large reductions in CO_2 can be attained with VCR technology.
- Criteria emission standards (HC, NOx, CO, Particulate) for gasoline VCR engines are attainable using proven 3-way catalytic converter technology.
- The Envera VCR mechanism has several benefits:
  - A large enough VCR travel distance (+7.6mm)
  - Robust structure for supporting ~30 bar bmep loads
  - Minimal friction loss penalty
  - Approximately stock engine size (can fit into existing engine bays)
  - Stock cylinder heads can be used with the Envera VCR crankcase
  - Low cost high-volume production
  - Good match with production transmissions. 7000 rpm design speed. “Down-speeding” not required.

Thank you

US Department of Energy
National Energy Technology Laboratory

Partners and Program Donors:

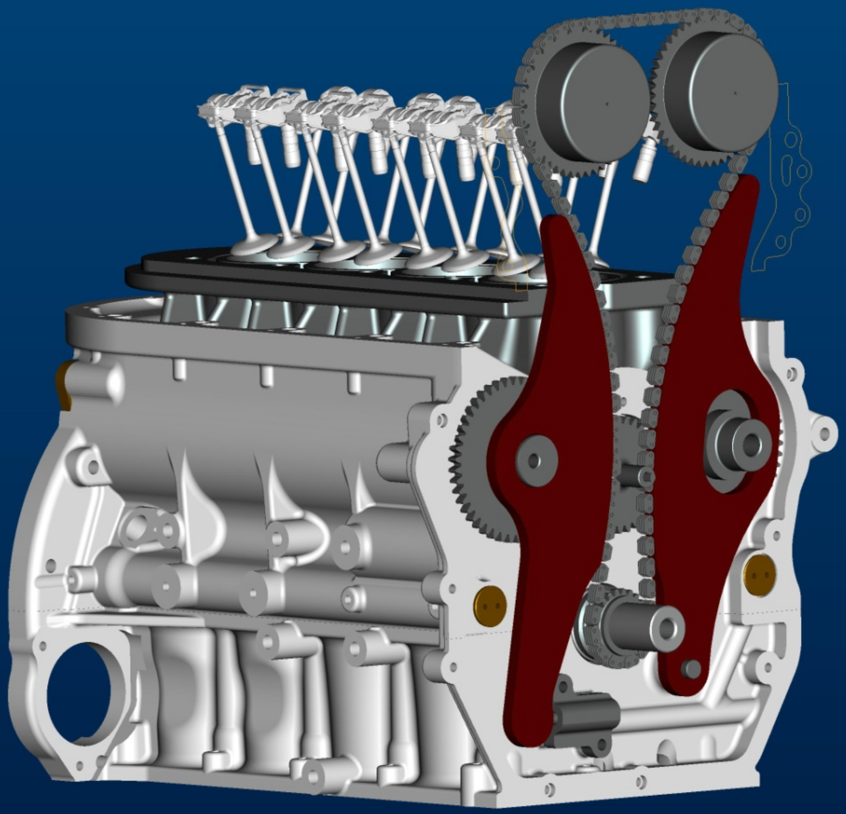
- Envera LLC
- Eaton Corporation
- MAHLE Powertrain
- Gamma Technologies
- EngSim Corporation
- ADEM LLC
- Hasselgren Engineering

Charles Mendler
ENVERA LLC
Tel. 415-381-0560
CMendler@VCREngine.com

Technical Backup Slides

Envera VCR

High CR



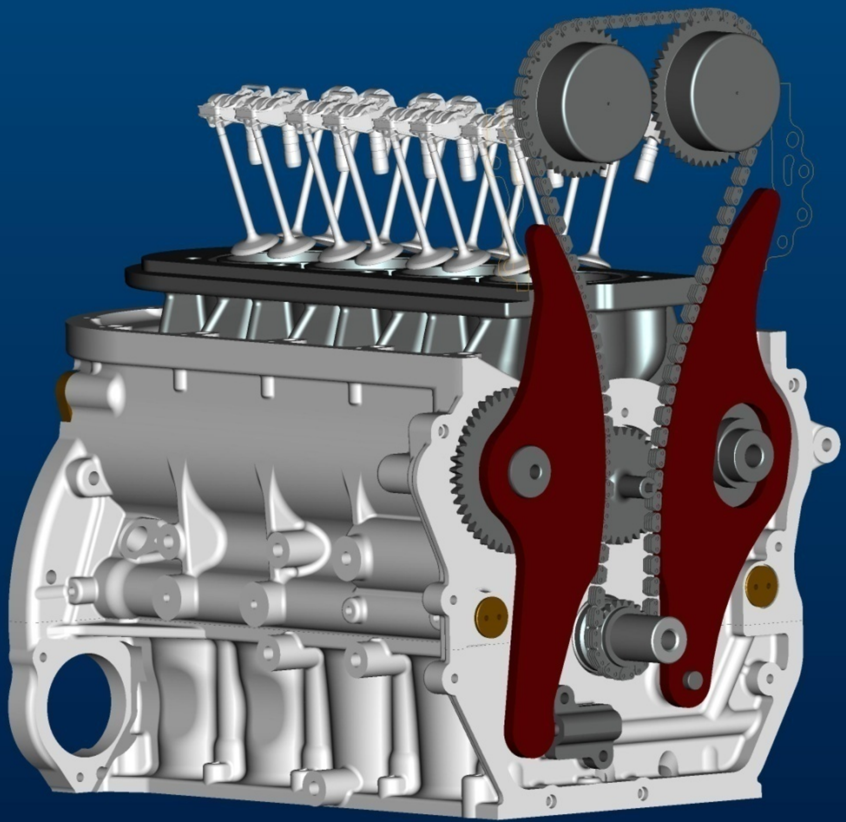
The control shafts position the chain guides

The cam timing can change with change of CR. OE options include:

- Advance of timing
- Retard of timing or
- No change at all.

Envera VCR

Low CR

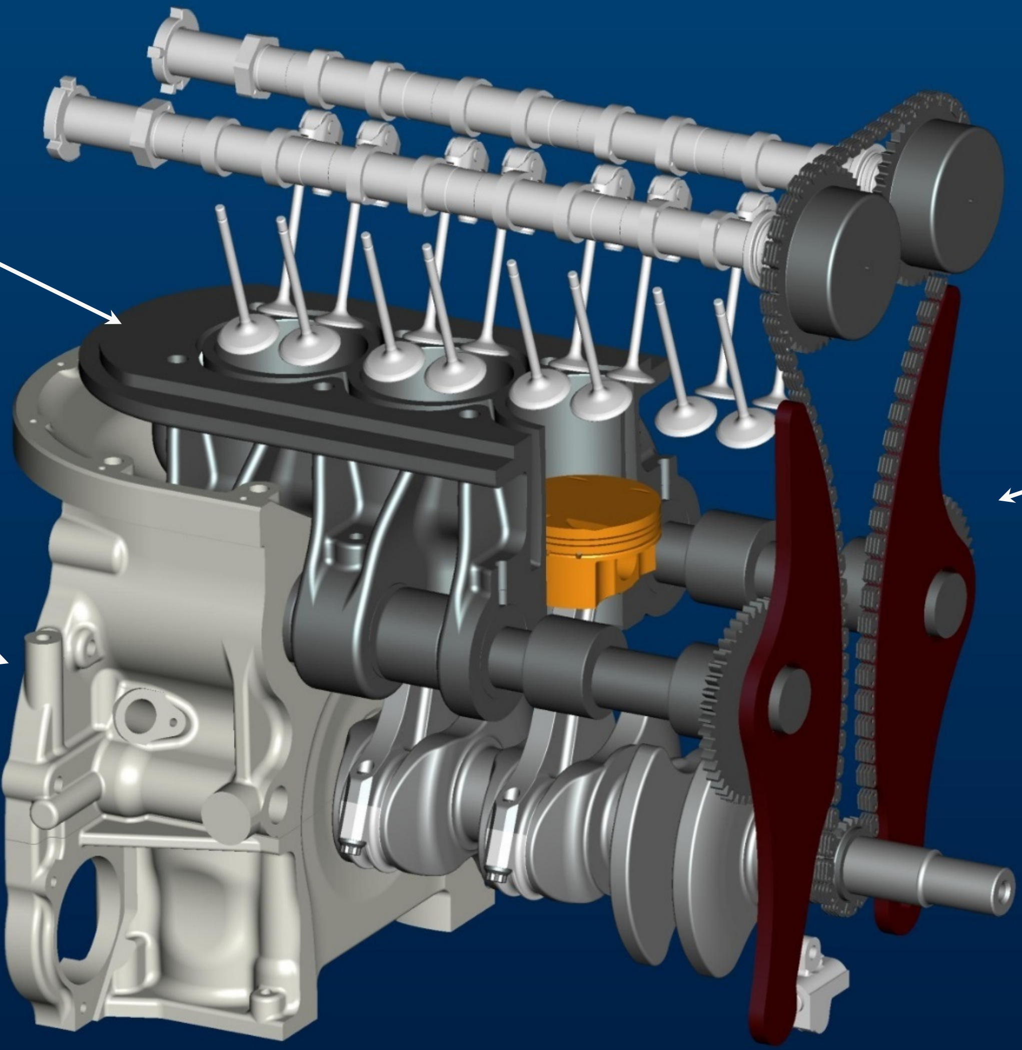


Camshaft chain drive friction is about the same as non-VCR engines.

Envera VCR

Cylinder jug*

Aluminum crankcase

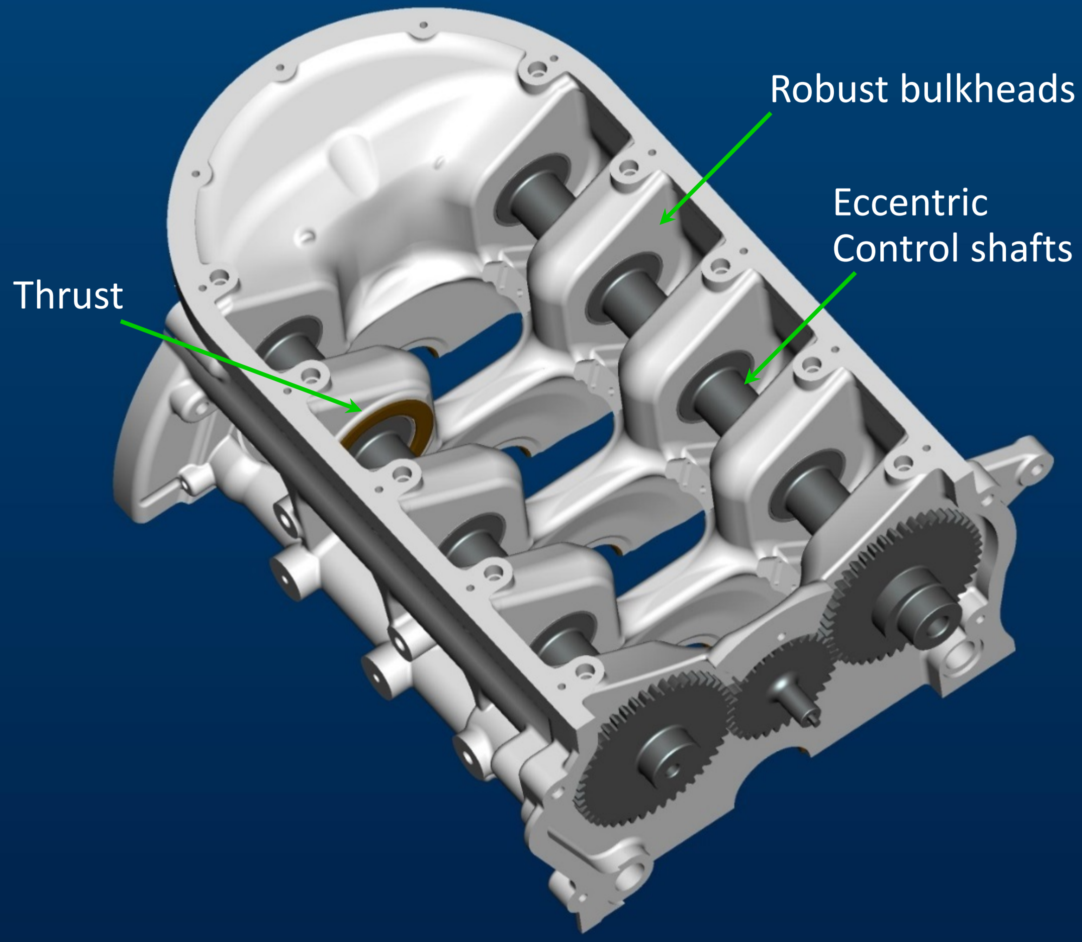


The two control shafts are used to adjust compression ratio

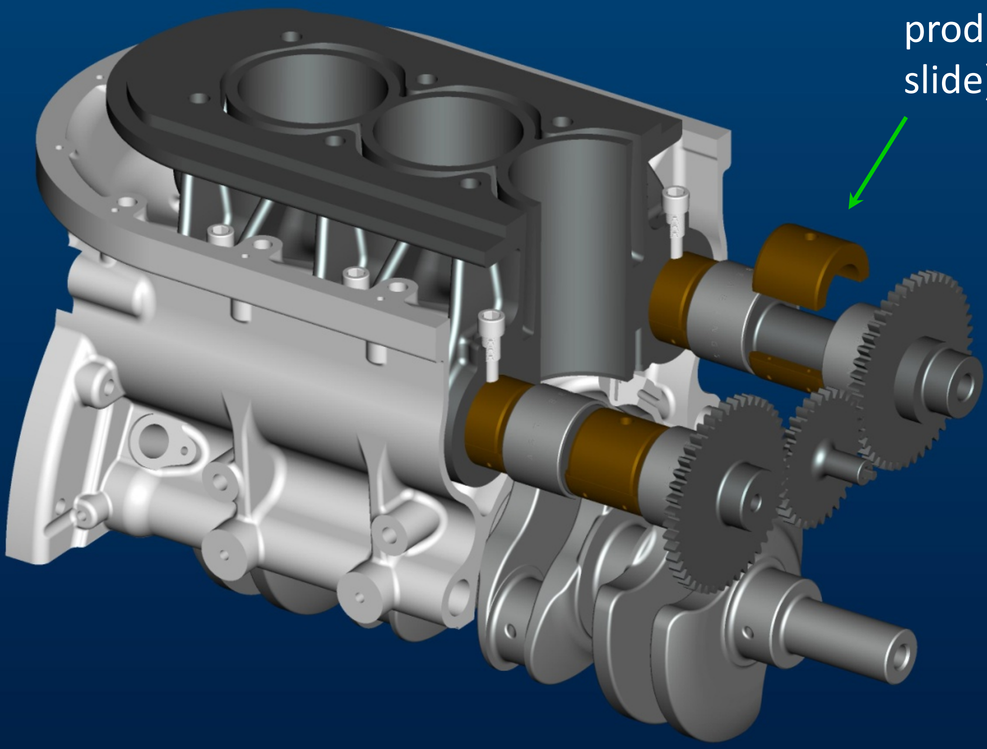
*Aluminum cylinder jug with cast in place liners for production. Iron jug for first prototype.

Envera VCR

Upper crankcase



Envera VCR



Assembled bushings for prototype.

Shrink-fit bushings for production. (See backup slide)

Eaton Variable Valve Lift

Eaton VVL Rocker Arm

Optimized

Multiple valve lift profiles

The VVL rocker arm to 6800rpm

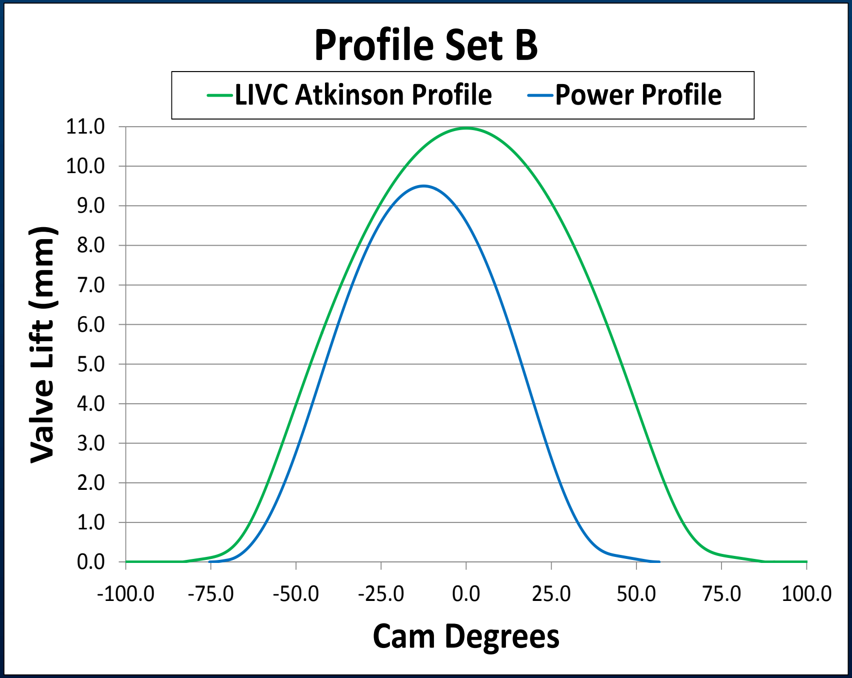
Results

VVL performance meets requirements

Exhaust SRFF meets requirements

Status

Fabricating cylinder head, cams, and VVL rocker arm hardware

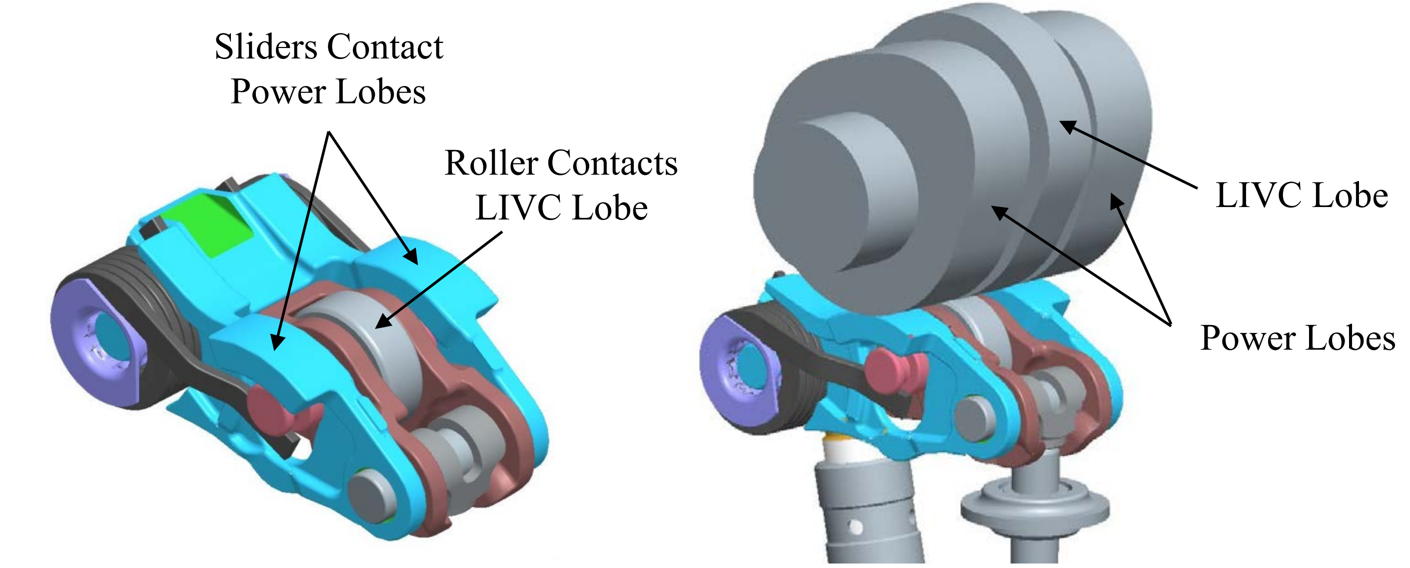


Eaton Variable Valve Lift

Phase 3 Optimization – *Under review*

Over-all fuel economy can be increased by using the roller follower for the Atkinson Cycle, and the slider contacts only for power and torque.

The current build uses sliding contact for the Atkinson Cycle. The roller follower Atkinson design is shown below.



LIVC Low Friction Rocker Arm For Atkinson Cycle Operation

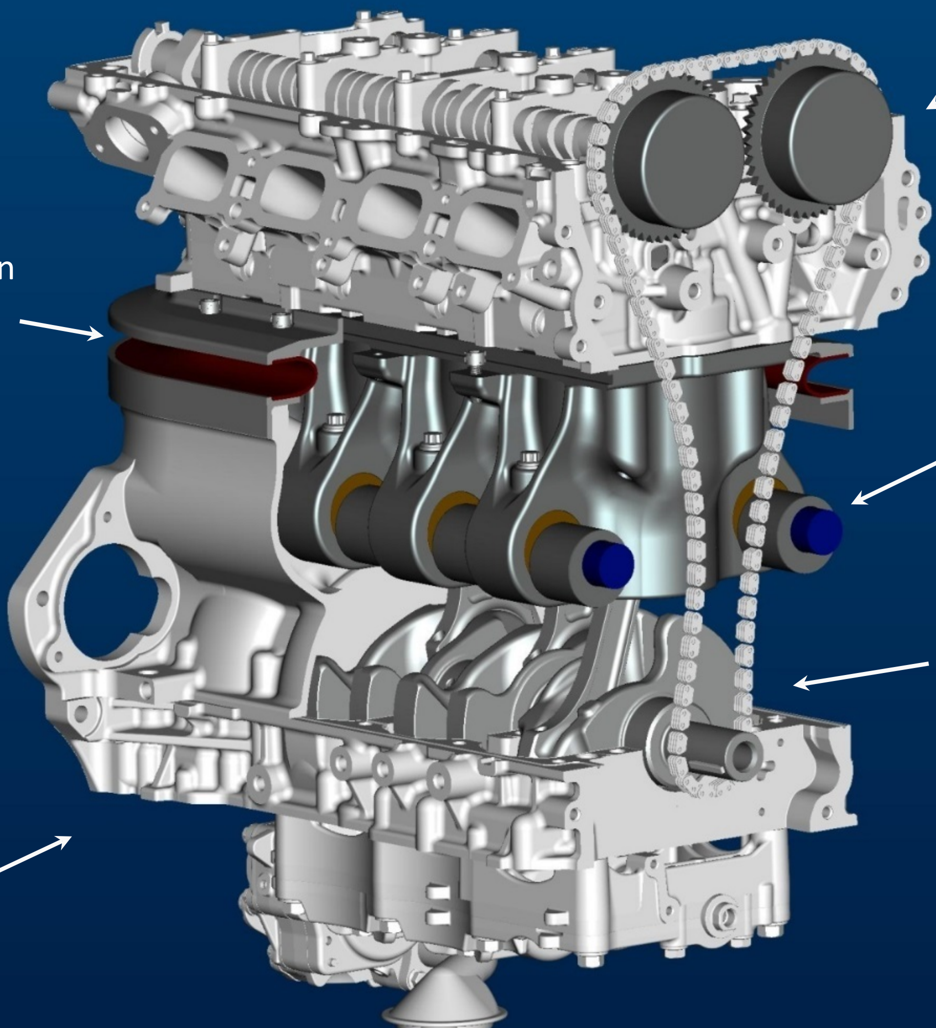
Envera VCR 2.0 – Backup Slide

Earlier version shown

Nitrile gasket:

The Nitrile curtain is bonded to steel flanges. The bond is stronger than the curtain.

Affordable: Low-volume production quote of $42 each on order of 10,000 pieces.



Stock cylinder head with Eaton VVL & Atkinson cycle cams

Rotating the control shafts adjusts compression ratio from 8.5:1 to 18:1

The VCR mechanism doesn't add mass to the cranktrain. High engine speeds and loads attainable with conventional and reliable cranktrain technology.

~Stock engine length:

Stock bedplate and crankshaft. Stock starter motor and bell housing flange.

Compression Ratio Values

High CR needed for Atkinson Cycle efficiency

Low CR needed for multiple reasons:

Minimum compression ratio	8.2:1

A low compression ratio is needed for:

- Preventing detonation (knock)
- Limiting the rate of pressure rise to minimize combustion harshness
- Reducing turbocharger lag (Time-to-torque)
- Increasing boost pressure and engine torque at low engine rpm
- Reducing main and rod bearing size for lower fmep

Compression Ratio Values

High compression ratio:

Maximum compression ratio	17.6:1
Bore/Stroke ratio	0.9
BSFC target 100 Nm 2000 rpm	230 g/kWh

High compression ratio engines need a small bore to stroke ratio for minimizing combustion chamber surface area and minimizing heat loss.

Increasing CR from 16.5 to 17.5 requires an additional VCR travel of only 0.38mm (0.015 inch). The higher CR value will be used because it will return higher efficiency with no real down side to the engine design.

Compression Ratio Values

VCR Mechanical Travel:

The VCR mechanism needs to provide a mechanical travel range of about 8.0 mm.

ENVERA 2.4L VCR Engine				
VCR Travel Needed			Build 1	Build 2
Bore		mm	88.50	88.50
Stroke, S		mm	97.50	97.50
Bore/Stroke			0.908	0.908
Cylinder displacement		cc	599.8	599.8
Cylinders			4	4
Engine displacement		L	2399	2399
CR				
	Max		17.50	17.50
	Min		8.22	8.00
Chamber volume, d				
	Max CR	cc	36.35	36.35
	Min CR	cc	83.07	85.68
Change in volume		cc	46.72	49.33
VCR Travel, T		mm	**7.6**	**8.0**

Emissions

Approach for attaining low criteria emissions

- Lambda 1 fuel/air mixtures used with 3-way catalytic converter technology and EGR for low HC, CO and NOx emissions.

Proven strategies to be employed.
Gasoline & alternative spark-ignition fuels.

AMR Presentations 2014 & 2015	Chrysler[1]	Ford[2]	Envera[3]
Light load BSFC 5.25 bar bmep @ 2000 rpm	~250	~245	230
Power Maximum kW/L	56.3	80	~118

1. AMR 2014/2015: Results - Performance, pg. 6 Engine Efficiency, bsfc, pg. 9
2. AMR 2014/2015: Attributes and Architecture, pg. 7. Fuel consumption, pg. 13. Ford data interpolated by Envera.
3. Targets

Patent references

Companies sighting Envera / Mendler patents – Partial listing:

BorgWarner	Caterpillar
Cummins	Daimler Chrysler
DENSO	FEV
Ford	GE
GM	Hitachi
Honda	INA
Izuzu	MTU
Nissan	Pinnacle / Cleeves
Polaris	Suzuki
Toyota	Visteon
VW	Yamaha

There's interest in what we're doing